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Current and future flood risk of new build homes across different socio-economic neighbourhoods in England and Wales

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E-mail: v.roezer@lse.ac.uk**Keywords:** flood resilience, exposure, spatial planning, climate change

Abstract

Despite improvements in the management of flood risk and the introduction of new regulations, losses from flooding remain high. An important driver is the continuation of new assets being built in flood prone locations. Over the last decade over 120 000 new homes in England and Wales have been built in flood prone areas. While the yearly rates of new homes in flood risk areas have increased only moderately on the national level, significant differences between and within regions as well as between different flood types exist. Using property level data on new homes built over the last decade and information on the socio-economic development of neighbourhoods, we analyse spatial clusters of disproportional increase in flood exposure from recently built homes and investigate how these patterns evolve under different future climate scenarios. We find that a disproportionately higher number of homes built in struggling or declining neighbourhoods between 2008 and 2018 is expected to end up in areas at a high risk of flooding over their lifetime as a result of climate change. Based on these findings, we discuss issues regarding future spending on flood defences, affordability of private level flood protection and insurance as well as the role of spatial planning for adaptation in the face of climate change.

1. Introduction

Flood risk is commonly understood as a function of hazard, exposure and vulnerability and can be altered through de- or increasing any of the three components [1]. The largest share in increases in flood risk and subsequent losses over the last decades in many areas of the world including the UK can be mainly attributed to an increase in exposure [2], but is likely to be exacerbated by climate change (CC) through an increase in extreme rainfall events and the mid- to long-term effects from sea level rise [3].

Therefore, managing the creation of new risk through spatial planning and other incentives that aim to reduce the amount of new assets in flood prone areas (including areas that are likely to become flood prone in the future) is seen as a key component of long-term flood risk management and adaption [4].

At the same time altering the flood vulnerability of communities by making people and assets more resilient to flooding through adaptation and efficient recovery is increasingly included in national

policies and local flood risk management practice [5]. In the context of flood risk management and adaptation the term resilience has been defined differently, but a common distinction also used in this study is between asset-level engineering resilience and system-level community resilience [6–8]. Engineering resilience describes in this context the design (e.g. use of flood resistant materials, elevated floors etc) and use of buildings, that aim to prevent any harmful impacts from flooding on the asset level. Community resilience describes the ability of communities on a system level to withstand, adapt to, and recover from shocks (such as a flood event) in a way that it enables them to pursue their social, ecological and economic development objectives [8, 9].

With a shift of the responsibility towards private households and businesses to manage their own flood risk over the last decades, the question of an uneven distribution in the capacity of communities or neighbourhoods and individuals to respond to and recover from flooding in the context of environmental justice and resilience to flooding is emerging in both the

academic literature and policy debate [10, 11]. This also includes discussions on the implications for spatial planning, with a growing recognition of the importance of underlying local differences in social vulnerability. Resilience in this context is criticised to be often interpreted or misused as an attempt to attenuate existing issues of environmental justice rather than challenging the underlying paradigms that caused them [12, 13].

In the context of social vulnerability and environmental justice, several studies linking local deprivation with flood exposure have been conducted in the UK [14–20], the US [21, 22] and elsewhere [23].

However, only few studies have analysed the long-term changes under the effects of CC and no studies are available that provide an empirical analysis that captures the effects of recent spatial planning decisions on the dynamic changes in flood exposure in interaction with differences in the development of local communities in the context of CC.

Yet, understanding the long-term effects of new properties and their flood exposure in the context of the wider socio-economic development of communities is an essential step to be able to consider long term community resilience in planning decisions. This is especially important in cases where trade-offs exist between the anticipated stimulation of the local economy through investments in the property market and the long-term effects of an increase in the exposure to flooding in a community. Not taking these trade-offs into account by not considering the system-level resilience of communities they are built in, in a forward looking way, can jeopardise the long-term sustainability of entire neighbourhoods.

This also applies to cases in which asset-level engineering resilience is the main strategy to ensure long-term sustainability as the relevant property-level measures might be attenuated or waived during the planning process to not threaten the economic viability and affordability of new property developments or might become less effective in case of changing hazards under CC [24].

In this paper, we address this lack of evidence on the long-term effects of recent increases in flood exposure in the context of community resilience for the example of England and Wales by investigating (a) where new homes have been built between 2008 and 2018 in England and Wales geographically and over time, (b) how they are contributing to the current and future flood risk of their neighbourhoods, and (c) how the socio-economic development of the neighbourhoods they have been built in might affect their resilience to flooding under changing flood hazards as a result of CC.

We discuss how the findings in this study can support an improved spatial planning system by identifying neighbourhoods that, without further adaptation and efforts to increase community resilience, might face socio-economic tipping points such

as sudden large-scale out-migration [25] following a flood event, significant increases in mortgage defaults and foreclosures [26] or a drop in insurability with implications for systemic risk [27–29].

2. Background

Flood risk management has long been seen as an isolated task with the purpose to prevent harm to people and assets, mainly through structural defences that should keep the water out [30]. Devastating flood disasters over the last decades in the UK and elsewhere with structural flood defences failing led to increasingly risk based approaches [27, 31].

One component to manage floods in a risk-based approach is to avoid increases in exposure by shifting development to areas with the lowest flood risk probability [32]. In this context the Planning Policy Guidance Note 25 (PPG25) was introduced in 2001 in England and Wales making the environment agency a statutory consultee on applications for planning permissions in flood risk areas [33]¹. This should ensure that local planning authorities, who are largely independent in setting their local development plans, only permit new property developments in areas at risk of flooding if no other options are available, the sustainable benefits outweigh the increase in flood risk and that the new property developments are both resilient (i.e. asset-level engineering resilience) and resistant to flooding [35].

However, facing competing interests and institutional agendas such as constraints on building on protected land and pressure to meet national housing targets, new developments are frequently permitted in areas at risk of flooding. The Adaptation Committee of the UK's Committee on Climate Change estimated in 2019 that 54 500 new properties were built in flood zones between 2014 and 2017 [36]. While the planning system stipulates that new buildings should only be built in accordance with requirements to ensure their current and future (engineering) resilience to flooding, there are no nation-wide data sets available to monitor whether these requirements are met.

In addition, most of these requirements are based on current flood risk levels not taking into account a potential future increase in flood risk as a result of CC [24]. At the same time, the effectiveness of other attempts to disincentivise new homes in areas at risk of flooding such as the exclusion of homes built after 2009 from the national flood insurance pool FloodRE remains unclear [27].

There are significant gaps in the understanding on how new properties in or near areas at risk of flooding affect the wider long-term future

¹ The planning policies are likely to be superseded by new legislation currently discussed and outlined in the *Planning for the Future* White paper [34].

sustainable development and system-level resilience in the neighbourhoods and communities they are built in. This concerns both the potential changes to the flood hazard as a result of CC as well as local socio-economic changes over the lifetime of new property developments.

In this context, we analyse where new homes over the last decade have been built in areas at risk of flooding in England and Wales and investigate the links between the socio-economic development trajectories of the neighbourhoods they have been built in. We also investigate how CC might affect these new homes over their lifetime by applying three different CC scenarios as used by the UK Committee on Climate Change [37].

3. Materials and methods

We combine property level information on the location of new residential dwellings built between 2008 and 2018 in England and Wales from the Address-Base Premium dataset provided by Ordnance Survey (OS) with information on their current and future risk of getting flooded under three different CC scenarios as well as the socio-economic development trajectories of the neighbourhoods the new residential homes have been built in. The flood risk of a new home is determined by whether the geolocation of the property is inside an area at risk of flooding defined by the official risk maps for flooding from river and sea (RoFRS) as well as from surface water (RoFSW) available for England and Wales. The flood risk maps have national coverage, include local expertise, and take into account flood defences and their condition.

Homes are considered as being at a high to medium risk of flooding (HFR), when the property is in an area with a 1% (0.5% for sea) or higher annual chance of flooding. Properties are considered to be at a low risk of flooding (LFR) in case they are located in an area with a 1% (0.5% for sea) to 0.1% annual chance of getting flooded (for further details see appendices A.1.1 and A.1.2).

The change in the flood risk by the 2050s as a result of CC is estimated for the different flood types (sea, surface, river) across England and Wales based on three CC scenarios as defined by the UK Climate Change Committee (CCC) [38]: a lower end scenario based on a 2° change in global mean temperature (GMT) (2C), a 4 °C change (4C) and a worst case scenario (H++) which does not refer to a specific GMT, but is considered a credible high end change scenario. A total of 11 908 local impact areas with sizes ranging from 3 to 23 km² are defined across England and Wales to capture the local and flood type specific changes to the areas at risk of flooding for the different CC scenarios. Following the approach from [37] we derive impact functions for each of the local impact areas and flood types by counting the number of new build properties that would get flooded for a

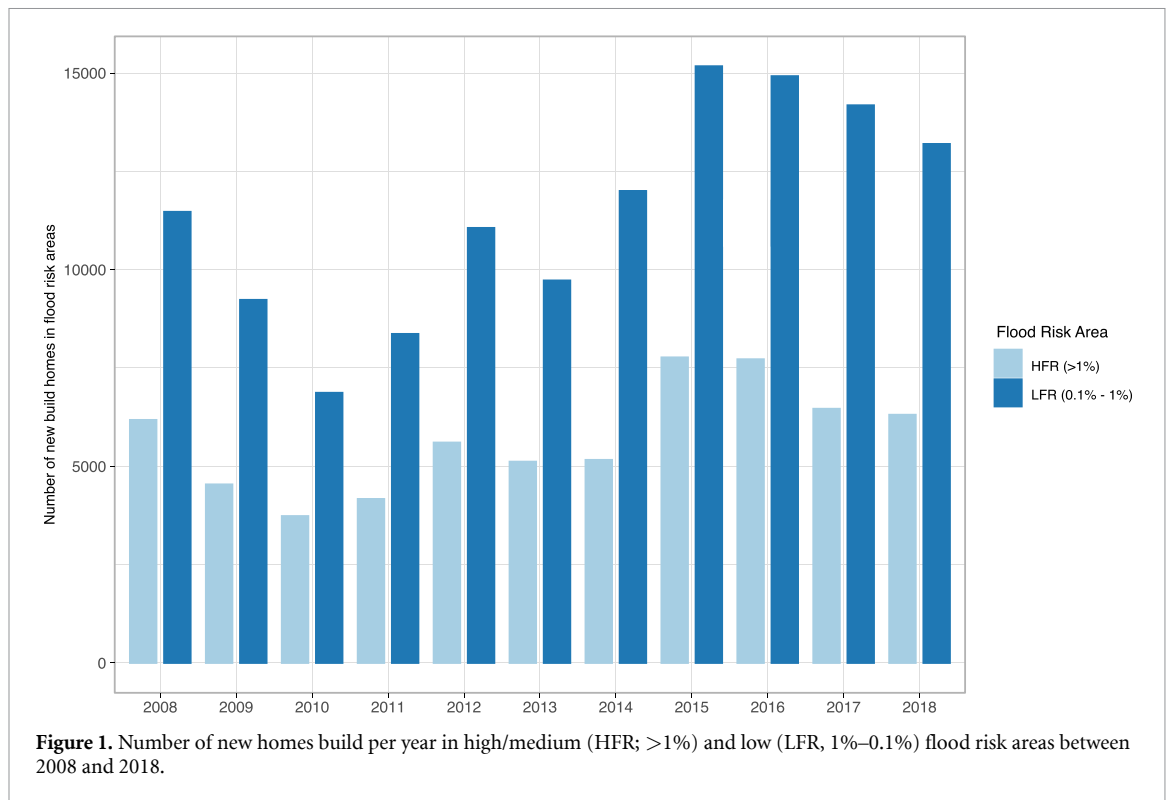
3%, 1% and 0.1% annual chance of flooding. Assuming no future changes in structural flood protection, we use the different regional scenarios for changes in the return period or standard of protection for river, sea and surface water flooding and the local impact functions to estimate the change in the number of properties built between 2008 and 2018 having a 1% or higher annual chance of flooding for each flood impact area by the 2050s for the three different CC scenarios (see appendix A.1.4 for details).

The information of the recently built homes and their current and future risk of flooding under CC is then combined with information on the socio-economic development of the neighbourhoods the homes have been built in. The neighbourhood development trajectory data set developed by [39] uses gridded information on demographic characteristics, socio-economic development and housing data of decadal censuses from 1971 to 2011 to first create representative neighbourhood typologies for each census year and then use sequence analysis to derive seven representative trajectories characterising the wider socio-economic development of neighbourhoods from longitudinal transitions of these neighbourhood typologies over time (see appendix A.1.3 for details). The data is available as a 1 km² grid for England and Wales.

In accordance with the three research questions outlined in section 1, we conduct three different analysis:

First, we analyse year to year changes in new homes in flood risk areas for the period between 2008 and 2018, both in total and by flood type. We use the non-parametric Mann-Kendall (MK) test to analyse trends in the absolute number and share of new homes in HFR and LFR. The non-parametric Theil-Sen estimator is used to estimate the magnitude and direction of both the national trend for England and Wales as well for each local authority (LA) district with the significance of the trend determined by a MK test [40]. The difference in slope from the Theil-Sen estimator between the national trend and the trend in each LA district is used as a measure for the strength of the local deviation from the national trend.

Second, we analyse spatial trends in flood exposure of homes built between 2008 and 2018. For that we analyse the number of new homes in HFR both for the current and the future flood hazard levels for the 2050s for the three CC scenarios. Hot spots are assessed by using local spatial auto-correlation. We use the local $G_i(d)$ statistic (local Getis Ord) to identify clusters [41] of local flood impact areas. For each local flood impact area the local $G_i(d)$ statistic is estimated based on the distance between neighbouring flood impact areas and both the respective absolute number and share of homes in HFR. The threshold distance for neighbouring flood impact areas was set that each area has at least one neighbour (see appendix A.2.1 for details).



Third, we analyse how the flood exposure of homes built between 2008 and 2018 is distributed among different socio-economic neighbourhood types. We calculate for each of the seven neighbourhood types the difference between the share of all new build homes and those in HFRs. This difference provides a measure whether the share of homes in HFRs for a specific neighbourhood type is higher (positive values), or lower (negative values) compared to what would be expected based on the overall distribution of homes built between 2008 and 2018 in the respective neighbourhood type. The difference is calculated for current and future flood risks under different CC scenarios to analyse how future changes in the flood hazard is affecting the recently built homes over their lifetime in different socio-economic neighbourhood types (see appendix A.2.2 for details).

4. Results

For the property data set, we find that for current hazard levels around 5% of the 1.3 million homes built between 2008 and 2018 in England and Wales are located in HFRs. Another 10% of new homes were built in LFRs. The majority of the 62 413 homes in HFRs are either affected by river (42%) or surface water flooding (41%). Full summary statistics are presented in table B1 in the appendix.

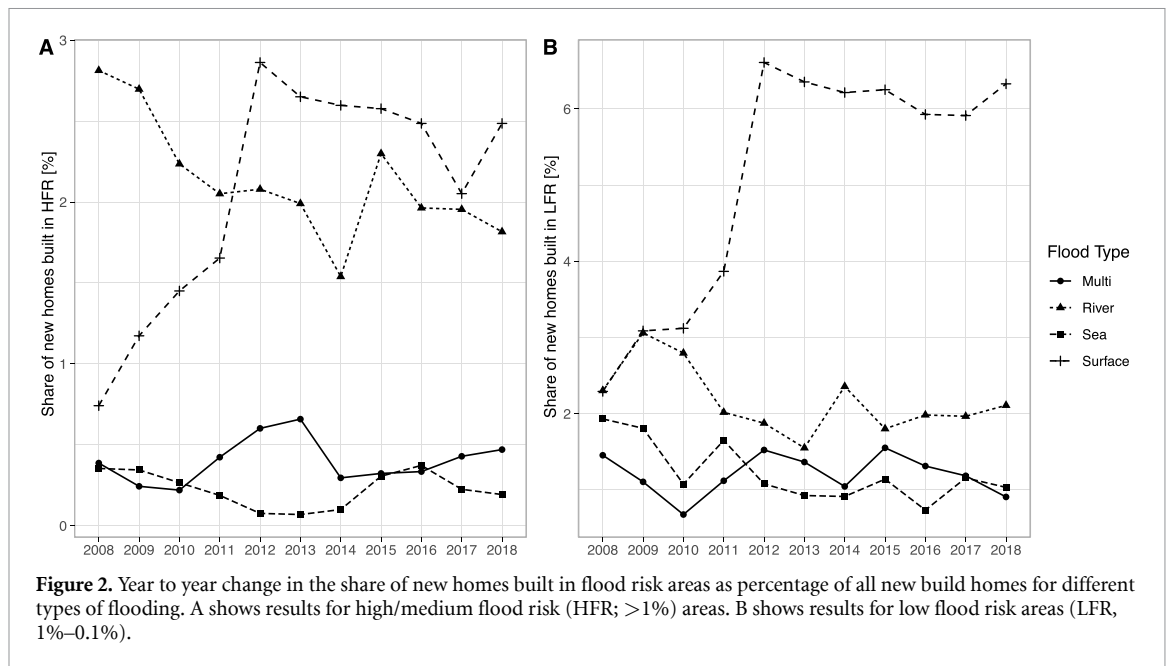
4.1. Time trends

We find significant trends for the year-to-year share of new build homes in flood risk areas in some local

authority (LA) districts. Of the 335 LA districts in which new homes have been built between 2008 and 2018, 29 show significant trends in the share of new build homes for HFR and 38 for LFR. Of those LA districts with significant trends seven LA districts for HFR and nine for LFR have trends below the national trend, while the majority of LA districts with significant increases have trends above the national trend. Only three out of the 335 LA districts have significantly declining trends in the share of new homes built in HFR and 8 LA districts in LFR. Figure B1 in the appendix shows all LA districts with significant year to year trends in the share of new build homes in flood risk areas including their deviation from the national trend.

For the absolute number of new build homes in flood risk areas in England and Wales between 2008 and 2018 we find a significant positive trend in LFR and no significant trend in HFR areas based on the MK trend test (90% confidence level)(see figure 1). When analysing the share of new build homes in flood risk areas in England and Wales for the same period we find no significant trends for both LFR and HFR areas (based on the MK trend test) (see figure B2 in the appendix).

Looking at the different flood types, we find that the rate of new homes built in areas at risk from surface water flooding has almost tripled between 2008 and 2012 and remains at a high level after reaching a peak in 2012, while the rate of new homes in areas at risk from river has decreased over time. Figure 2 shows the yearly rate of new build homes by flood type for HFR and LFR respectively. While the



available data does not allow for a detailed analysis of the reasons for the different year-to-year changes between different flood types, one influencing factor could be the introduction of flood maps and subsequent zoning regulations as part of the land use planning process to further restrict developments in areas at risk of flooding: flood risk maps for river and sea were formally introduced in today's shape and form in 2004, while surface water flood risk maps were first introduced in 2008 and updated in 2010 and 2013 [42], around the time when the rate of new homes at risk from surface water flooding starts to stabilise.

4.2. Spatial trends and hot spots

We find a high total number of new build homes in HFR in parts of London and in the Thames Valley for current hazard levels. Other clusters include urban areas in estuaries such as in Liverpool, Hull or Bristol as well as smaller areas along rivers in the East Midlands or Yorkshire and the Humber (see figure 3—top left).

Looking at the share of new build homes in HFR as a proportion of all buildings built in the respective area during the same period, a strong clustering with high shares appear mainly in estuaries on the border between the East of England and the East Midlands as well as along the river Trent in Yorkshire and the Humber (figure 3—top right). This is also confirmed by the hot spot analysis based on local spatial auto-correlation (figure 4): we find two significant local clusters with high shares of new build homes in HFR in estuaries on the border between the East of England and the East Midlands

and along parts of the river Trent. The latter was severely affected during the 2019/2020 winter flood season [43].

For the different CC scenarios we find that existing hot spots are expected to be further amplified with more homes built between 2008 and 2018 expected to fall into HFRs by the 2050s, increasing the share of new homes in HFRs in many areas without further action. But also new hot spots are expected to emerge without further intervention for these homes, especially along lower lying coastal areas in the South East of England, along the Thames river banks in London and along the Ouse in Yorkshire and the Humber (figure 3). We find the highest expected shift in the share of homes built between 2008 and 2018 in HFR by 2050 as a result of CC to range from 2%-points for the 2C scenario to 35%-points for the high-end scenario (H++). Here, the largest changes are expected along coastal areas and estuaries in the East of England and in Yorkshire and the Humber, but also in smaller areas in the South East and the North West of England. Results of the local hot spot analysis for different CC scenarios are shown in figure B3 in the appendix.

4.3. Current and future flood exposure by neighbourhood type

Figure 5 shows the distribution of homes in HFR built between 2008 and 2018 by the different socio-economic development trajectories of the neighbourhoods they have been built in (see section 3 and appendix A.1.3 for details on the socio-economic neighbourhood development data). When comparing to the overall number of homes built in the

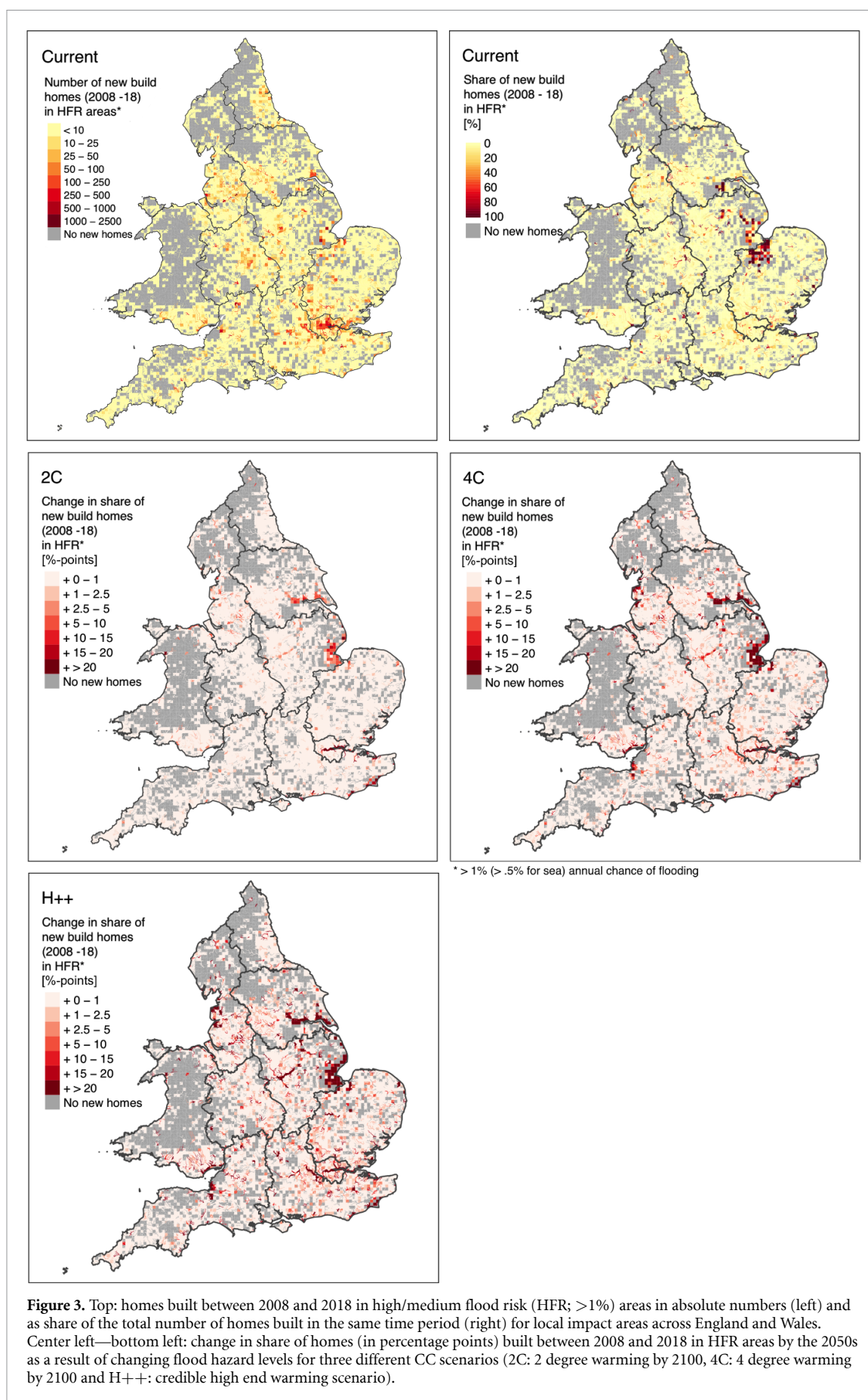
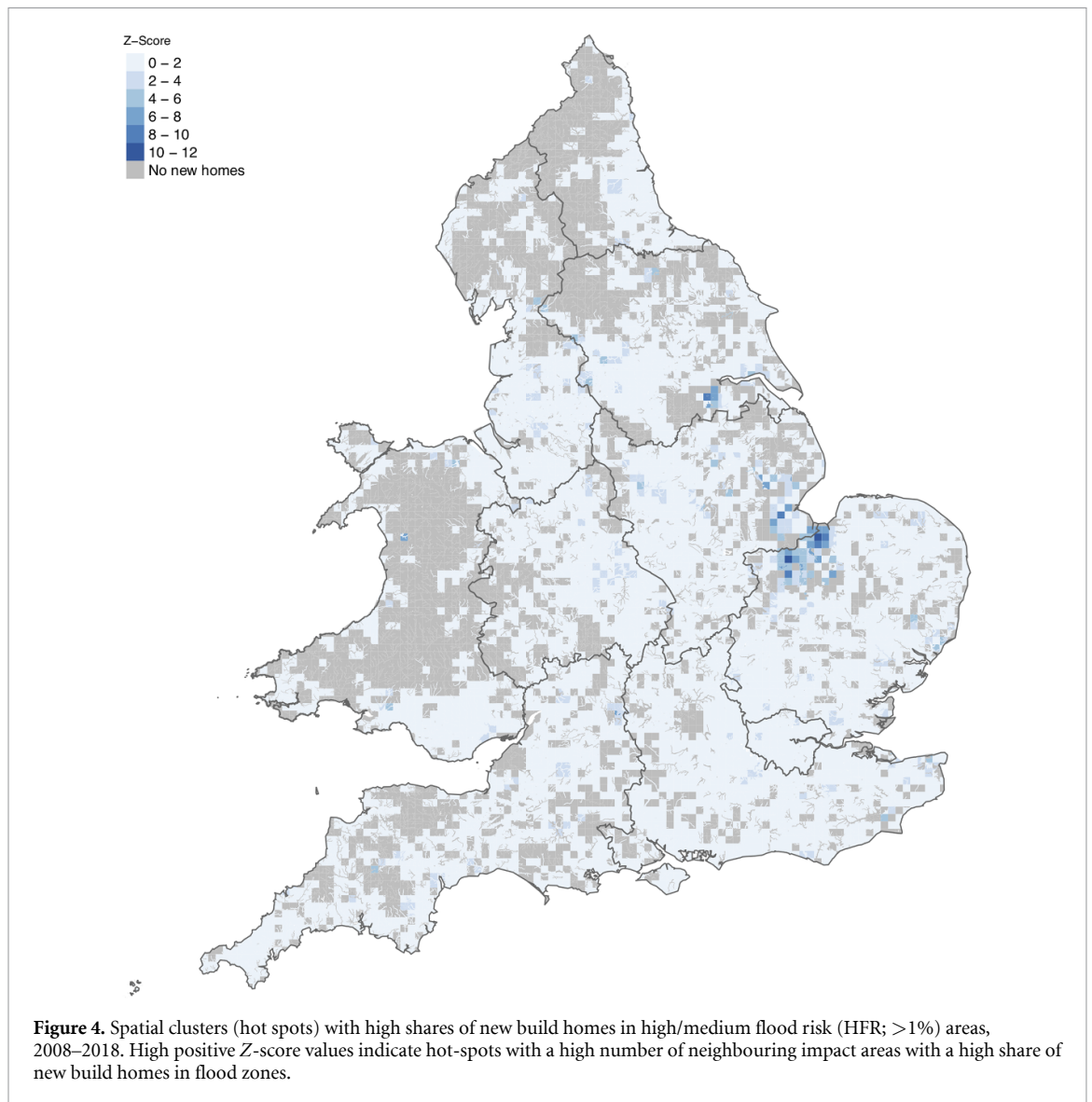
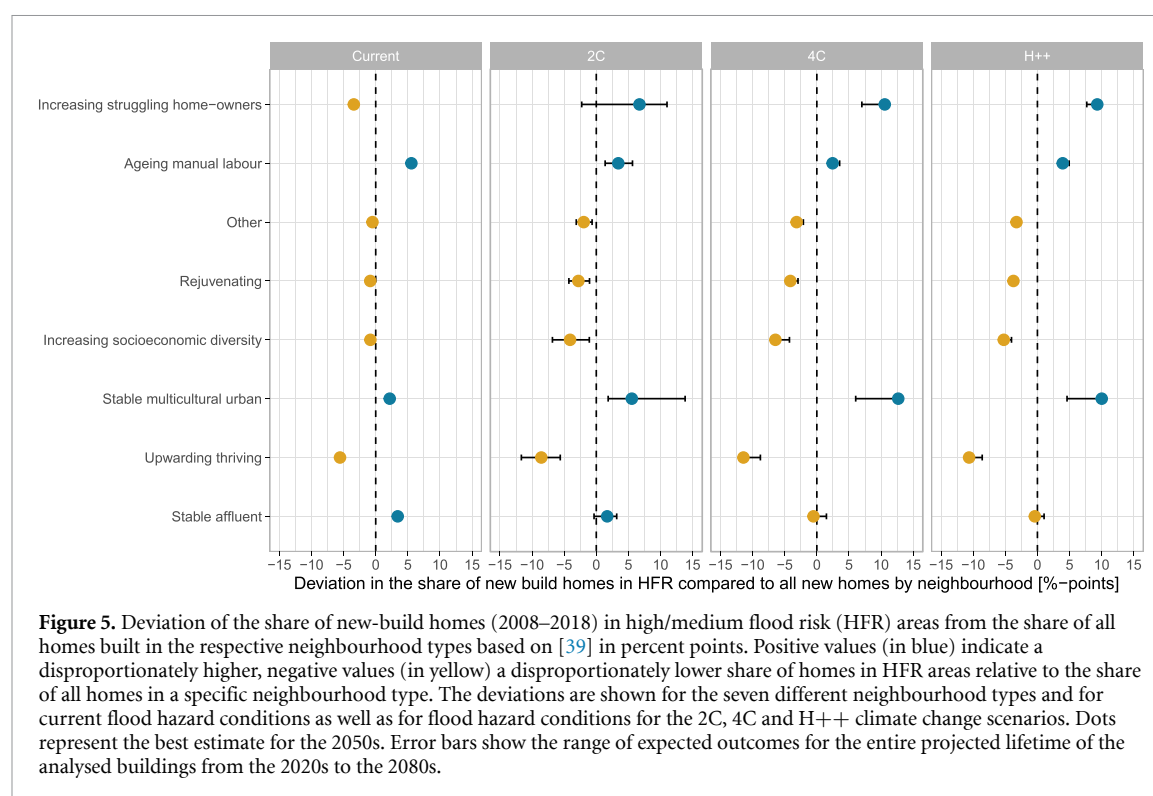


Figure 3. Top: homes built between 2008 and 2018 in high/medium flood risk (HFR; >1%) areas in absolute numbers (left) and as share of the total number of homes built in the same time period (right) for local impact areas across England and Wales. Center left—bottom left: change in share of homes (in percentage points) built between 2008 and 2018 in HFR areas by the 2050s as a result of changing flood hazard levels for three different CC scenarios (2C: 2 degree warming by 2100, 4C: 4 degree warming by 2100 and H++: credible high end warming scenario).



different neighbourhood trajectory types in the same period, we find that under current flood hazard conditions a disproportionately lower share of new homes in HFR in England and Wales were built in areas with *Increasing struggling homes-owners*, characterised by [39] as areas transitioning from a ‘families in council rent type to a struggling (home-owner) type’ as well as in *Upwarding thriving neighbourhoods*, described as neighbourhoods that have persistently been thriving over the last four decades. A disproportionately higher share of new homes in HFR were built in the *Ageing manual labour* (describing neighbourhoods transitioning from blue collar families to an ageing demographics type) and *Stable affluent* (describing neighbourhoods that have persistently remained affluent over the last four decades) neighbourhood types. For other neighbourhood types the share of new homes in HFR is nearly proportionate to all new homes built between 2008 and 2018 in those respective areas.

Under the assumption that neighbourhoods across England and Wales remain on their current socio-economic development trajectories over the coming decades, we find that the increase in the proportion of homes built between 2008 and 2018 exposed to flooding as a result of CC differs depending on the neighbourhood type they are located in. The results show a polarisation in the increase in the flood exposure of homes built between 2008 and 2018 over their lifetimes with increasing deviations in the share of homes located in HFR in three of the eight neighbourhood types (figure 5). Most noticeably in the *Increasing struggling homes-owners* neighbourhood type, where a CC induced change of the flood hazard is expected to lead to a disproportionately larger increase in the share of homes built between 2008 and 2018 ending up in a HFR by the 2050s for all CC scenarios, while its share under current hazard levels is disproportionately smaller.



5. Discussion and conclusion

Our study extends previous research on flood exposure, spatial planning and environmental justice [10, 11, 14–17, 19, 20] in the context of community resilience to flooding by including the effect recently built homes have on the flood exposure of different socio-economic neighbourhood types. We further investigate how changes in the hazard due to CC is affecting these homes over their lifetime in the socio-economic context of the neighbourhoods they were built in.

Our analysis shows that around 17 000 new homes have been built in HFR and LFR areas in England and Wales on average each year over the last decade. These homes are not only highly spatially concentrated with 34 local authority districts (10% of all local authority districts where new homes have been built) being responsible for 90% of all new homes built in flood risk areas, but also unevenly distributed between different socio-economic neighbourhood types. Our results indicate that a spatial shift in flood risk areas as a result of CC is expected to result in more homes built over the last decade to end up in HFR areas over their lifetime without further action. This increase is expected to be disproportionately higher in multi-cultural urban neighbourhoods and areas dominated by increasingly struggling home-owners.

It is difficult to consider all dynamic and mutually influencing processes when analysing the interplay between new build homes, current and future flood exposure and socio-economic development of

neighbourhoods in a forward looking analysis including the effects of CC.

Our study shows where new homes have been built between 2008 and 2018 and how their risk of getting flooded is changing over the coming decades in conjunction with changes in the socio-economic characteristics of their respective neighbourhoods. However, it is possible that the development trajectories of neighbourhoods might change in the future in case of significant disruptions. For example neighbourhoods might experience a change in investment flows (e.g. when a council decides it can no longer defend a neighbourhood from increasing flood hazards) [44] or simply as a result of changes in preferences or demand (e.g. raise in attractiveness of suburban or countryside homes). We partly address this issue by using a new data set of neighbourhood classifications from long-term longitudinal data [39]. This data set takes into account a larger set of variables characterising the longitudinal socio-economic development of different neighbourhood types over the last four decades and by that also helps increasing the robustness of development projections looking into the future. Other approaches use either proxy variables that are very sensitive to the overall economic development such as real estate prices or use relative measures such as the frequently used index of multiple deprivation (IMD), which does not allow longitudinal analysis over time.

Another source of uncertainty regards future changes in the flood hazard as a result of CC which is both affected by uncertainties in the link between changes in the GMT and the resulting changes in the

frequency and intensity of floods (e.g. through rising sea levels and changes in rainfall patterns). While we use highly localised flood impact areas across England and Wales to cover the different local impacts of CC on the flood hazard, assumptions need to be made on the functional relationship between the change in flood hazard levels and number of homes affected by this change (a more detailed discussion of the assumptions and limitations can be found in the appendix A.1.4).

Future investments in structural flood defences could offset some of the identified increases in hazard levels, but it is uncertain where and to what degree this can and will be done. However, as the current spatial planning regime works under the assumption that new homes in flood risk areas are built and designed to be able to resist flooding (by means of engineering resilience) over their expected lifetime, we do not consider any future changes in structural flood defences to specifically protect these homes.

As there are so far no regular assessments of the actual engineering resilience of individual new build properties and recordings if they meet the requirements set in the planning process, it remains uncertain to what extent the increase in exposure shown in this study can be offset by property level engineering resilience to avoid an increase in flood damage. While assumptions on the rate and effectiveness of for example private level adaptation have been made in previous studies, they generally rely on limited evidence and it remains unclear to what extent they reflect reality [45].

Based on the considerable differences in the change of flood exposure of new build properties between different neighbourhood types as a result of CC shown in this study, it is very likely that the socio-economic characteristics of these neighbourhoods are also closely linked to differences in their community resilience. In this context especially struggling communities with increasing flood exposure are likely to become less resilient to flood disasters without further action. While this study is a first step towards establishing an empirical link between the role of spatial planning decisions and the flood resilience and long term sustainable development of communities, more research is needed to better utilise spatial planning in supporting CC adaptation and community resilience as requested by the CCC and others [44, 46]. This also requires more research in supporting a better understanding and measurement of community resilience, which is still in its early stages [47, 48].

Such an approach also needs to include financial implications of community resilience: The majority of the homes in our analysis is not covered through the subsidised insurance pool FloodRE, due to the exemptions of homes built after 2009 and insurance cover may become unavailable or not affordable for these new build homes. In this context, previous studies have shown that changes both in

flood exposure and insurance premiums negatively affect property values, with expected negative effects on community resilience through reduced financial resources [49, 50].

Our results indicate that already struggling neighbourhoods will face this issue more likely than other types of neighbourhoods. This can lead to knock-on effects where a low or lacking ability to cope with increasing flood risks of individual households or properties can decrease both the attractiveness and property value of a larger area as chances for a full recovery after a flood event decrease and community development is impaired [25]. This could bear a wider risk with systemic implications such as an increase in mortgage defaults and foreclosures due to a combination of decreasing real estate prices and lower chances of financial recovery [26].

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We would like to thank Ordnance Survey for providing us with the raw data from which the new location of new build homes were derived. We also would like to thank Nikos Patias, Francisco Rowe and Stefano Cavazzi for allowing us to use their data set on neighbourhood development trajectories. We are grateful for peer review comments from Kathryn Brown and Paul Sayers as well as from the editor and two anonymous reviewers of this journal.

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Appendix A. Material and methods

A.1. Data

A.1.1. New build properties 2008–2018

We construct a property level data-set of newly build dwellings between 2008 and 2018 in England and Wales by combining information on the dwelling type, location, occupancy and postcode from the AddressBase Premium product provided by Ordnance Survey [51] with postcode information from the publicly available postcode directory from the Office of National Statistics (ONS) [52] through their unique post code. AddressBase Premium contains detailed information on address and types of

assets for every property in the UK. By filtering the dataset by the property type and the introduction year of a new postcode from the ONS postcode directory, we are able to identify new residential homes and the year of their completion (i.e. the year the address has been activated). The resulting data set comprises of around 1.3 mio data points representing new homes in England and Wales built between 2008 and 2018, their year of completion, their location and the dwelling type (flat, detached, semi-detached, terraced, other). This approach is different from previous approaches such as by [53], which compared reversed versions of the AddressBase data base for specific snapshots in time, to allow for a higher temporal resolution.

The constructed data set contains both new developments on green- and brown fields associated with land-use change as well as conversions or redevelopments in existing urban structures. Individual homes are defined as self-contained units with their own registered address. The data set has been validated by comparing historic high-resolution satellite imagery from GoogleEarth from a year before and after the stated year of construction for 50 random addresses.

A.1.2. Flood hazard maps

The flood hazard maps used in this study are the publicly available flood maps provided by the Environment Agency for England and by Natural Resources Wales for Wales. For the flood hazard from river and sea the 'Risk of Flooding from Rivers and Sea (RoFRS)' flood maps are used [54, 55]. For surface water flooding the extent maps from the Risk of Flooding from Surface Water (RoFSW) are used [56, 57]. The flood maps have nation-wide coverage, are available as GIS shapefiles and shows the chance of flooding as one of four flood risk categories, taking into account flood defences and their condition.

In this study we consider homes being at a high/medium risk of flooding, when the property is in an area with a 1% or higher annual chance of flooding from river and surface water and a 0.5% or higher annual chance of flooding from sea. We consider areas with a low risk of flooding in case they have between a 1% (0.5% for sea) and 0.1% annual chance of getting flooded. Whether a home is at risk from flooding is determined by its location within or outside the respective flood risk area.

A.1.3. Neighbourhood development

To identify the development trajectories of neighbourhoods in combination with their flood exposure, we use a gridded, spatio-temporal consistent neighbourhood trajectory data set developed by [39]. The data is available on a 1 km² grid for England and Wales. The approach uses neighbourhood-level information of the four decadal censuses between 1971 and 2011 to create neighbourhood typologies for each census

year. The neighbourhood typologies are based on in total 21 variables on demographic (age, place of birth), socio-economic (socio-economic group, occupation, proportion of students, unemployment, mode of travel to work) and housing data (ownership, social housing, vacancy rate) (a full list and of all variables considered in the analysis is shown in [39]). Sequence analysis was used to derive seven representative trajectories of neighbourhood development from longitudinal transitions of these neighbourhood typologies over time. The names and descriptions of the seven trajectories are shown in table A1. This approach allows for a spatially and temporally consistent and representative classification of development paths of neighbourhoods in a community, identifying neighbourhoods with stable, upward and downward socioeconomic development pathways. Compared to the widely used English and Welsh indices of multiple deprivation (IMD), which only allow to analyse changes in deprivation between two snapshots in time relative to other neighbourhoods, sequence analysis allows to capture the evolution of neighbourhoods transitioning through phases of development, growth, stability and decline over time. More details on the methodology that was used to derive the representative trajectories can be found in [39]. For the analysis in this study, the neighbourhood a new home was built in is determined by its geographical location. In cases where new developments are not in a neighbourhood trajectory grid cell (either through small inaccuracies caused by the grid approach or through greenfield developments that have not been considered as part of the neighbourhood before) we apply a nearest neighbour approach to link the new build homes to the nearest neighbourhood. This is only done in cases where the new build home is less than 1 km (or 1 grid cell) away from the closest neighbourhood, based on the assumption that developments further away need to be considered as independent new neighbourhoods which are likely to have their own development trajectories.

A.1.4. Climate change scenarios

For this study the future flood hazard projections for three CC scenarios for the 2050s as defined by the UK Climate Change Committee (CCC) are considered [38]: a lower end scenario based on a 2° change in Global Mean Temperature (GMT) (2C), a 4°C change (4C) and a worst case scenario (H++) which does not refer to a specific GMT, but is considered a credible high end change scenario. All changes in GMT are expressed for the year 2100 relative to the 1961-90 baseline as by the UK Climate Change Projections (UKCP09) provided by the Met Office. Based on these climate projections [37] developed future flood hazard projections for the UK including relative sea level rise around the English and Welsh coastline, changes in peak river flows for the 12 major catchment areas in England and Wales as well as changes

Table A1. Names and key features of the seven main neighbourhood trajectories as described in [39].

Neighbourhood trajectory name	Description
Stable affluent	Areas remaining persistently affluent over 1971 and 2011.
Ageing manual	Areas transitioning from being dominated by blue collar families to an older striving neighborhood type.
Increasingly socio-economically diverse	Areas transitioning from a struggling or blue collar families type to a mixed workers suburban type.
Increasingly struggling home-owners	Areas transitioning from a families in council rent type to a struggling type.
Stable multicultural urban	Areas remaining multicultural in urban locations.
Rejuvenating	Areas transitioning from an older striving type to a mixed workers suburban type.
Up-warding thriving	Areas transitioning from an older striving type to, or remaining in, a thriving suburban type.

Table A2. Regional differences and differences in susceptibility considered in the three different climate change scenarios.

Flood type	Change indicator	Regional differences	Susceptibility differences
Sea	Relative sea level rise	5 coastal regions (E, SE, SW, MW, NW)	3 coastal defence types (sea wall, embankment, beach)
River	Peak river flow	12 hydrometric regions	—
Surface	Storm rainfall depth & intensity	—	2 runoff types (rural, urban)

in storm rainfall depth and intensity influencing the surface water flood risk. Using the same approach and assumptions as in [37] for the UK Climate Change Risk Assessment the relative changes in sea level rise, peak river flow and storm rainfall depth and intensity are translated into changes in the annual chance of flooding/changes in the level of protection for different hydrological regions, land use types (i.e. urban and not urban) and coastal regions and features (i.e. beaches, cliffs, levees etc). Change parameters for all flood types, different return periods and the different scenarios used in this study can be found in [58]. Table A2 gives an overview of the regional differences and differences in the susceptibility for the different flood types considered in this study. To analyse the potential local effect of CC on the future exposure to floods of new build properties, we create local impact areas based on a 5 by 5 km grid across England and Wales for surface water flooding. For sea and river flooding, we use the same grid to split areas potentially affected by flooding from river or sea (based on current shapefiles of flood risk areas from the RoFRS). This allows us to define a total of 11 908 local flood impact areas across England and Wales with sizes ranging from 3 to 23 km², that are spatially consistent in regard to their flood risk. Based on the mentioned regional CC parameters we derive impact functions for each flood type and for each of 11 908 local impact areas. The impact functions describe the functional relationship between the current annual chance of flooding (i.e. 3%, 1% and 0.1%) and the respective number of homes built between 2008 and 2018 at risk from flooding. The impact functions are then used to translate the change in the flood hazard for the three different CC scenarios into the change in the

number of homes that are expected to have 1% or higher annual chance of flooding by the 2050s under the 2C, 4C and H++ scenarios. To do that, we assume linear relationships between the change in the area with a 1% or higher annual chance of flooding and the additional number of homes that fall into that area.

For the hypothetical example of a local impact area with 10 homes with currently a 1% or higher annual chance of flooding from sea and an additional 20 homes with currently an annual chance of flooding from sea between 1% and 0.1%, the expected shift in the number of houses at 1% or higher annual chance of flooding as a result of climate change would be estimated as follows: based on the CC scenarios for that area sea level rise is expected to lead to a shift in flood probability so that the equivalent of a 1% or higher annual chance of flooding in the 2050s would be the equivalent of 1.2% or higher annual chance of flooding today. This 20% increase for the equivalent of a current 1% or higher annual chance of flooding is estimated to lead to a 20% increase in the number of homes that are currently in the next higher risk band, i.e. the 20 homes that currently have between a 1% and 0.1% annual chance of getting flooded. With 10 homes already with a 1% or higher annual chance of getting flooded and an additional 20% of the 20 homes with currently an annual chance of getting flooded between 1% and 0.1%, the estimated number of home with a 1% or higher annual chance of flooding in the 2050s is 14.

This approach assumes that homes in higher risk bands are randomly distributed in space within the spatial area of that risk band. This assumption needed to be made as currently no consistent flood risk maps with national coverage are available that show

expected changes in flood probability for a location in high spatial resolution. However, as this approach is applied individually to the 11 908 local flood impact areas with high spatial resolution (3–23 km²), the effect of this simplification on the uncertainty of our results are expected to be small.

A.2. Methods

A.2.1. Spatial trends

We calculate for each local flood impact area i across England and Wales the share of homes in high/medium flood risk areas (HFR; >1% annual chance of flooding for river and surface, >0.5% for sea) P_{fi} by taking the ratio between the number of homes that have been built in HFR areas from 2008 to 2018 $N_{i,HFR}$ and the total amount of homes built in the respective flood impact area $N_{i,total}$:

$$P_{fi} = \frac{N_{i,HFR}}{N_{i,total}}$$

P_{fi} is calculated for the current climate, as well as for the 2C, 4C and H++ CC scenarios. To estimate the potential change in the spatial distribution of the share of recently built homes in flood risk areas by the 2050s, we calculate the difference in percent points between the current share and the share for the three different CC scenarios:

$$P_{fi,diff} = P_{fi,CC} - P_{fi,current}$$

Hot spots and spatial trends are assessed by using local spatial auto-correlation. We use the local $G_i(d)$ statistic (local Getis Ord) to identify clusters [41]. For each local flood impact area the local

Getis Ord statistic is estimated based on the distance between neighbouring flood impact areas and both the respective absolute number and share of homes in HFR areas. The threshold distance for neighbouring flood impact areas was set that each area has at least one neighbour.

A.2.2. Flood exposure and neighbourhood development

For each of the seven neighbourhood development trajectories across England and Wales, we calculate the deviation between the proportion of homes built in HFR areas with the overall proportion of homes build in each neighbourhood type:

$$\begin{aligned} \text{Diff}_{\text{per,nbh}} &= P_{\text{HFR,nbh}} - P_{\text{total,nbh}} \\ &= \frac{N_{\text{HFR,nbh}}}{N_{\text{HFR,total}}} - \frac{N_{\text{total,nbh}}}{N_{\text{total}}} \end{aligned}$$

with $\text{Diff}_{\text{per,nbh}}$ representing the difference in percent points between the share of new build homes in HFR areas for a specific neighbourhood type $P_{\text{HFR,nbh}}$ and the total share of homes for this neighbourhood type $P_{\text{total,nbh}}$. $\text{Diff}_{\text{per,nbh}}$ provides a measure whether the share of homes in flood risk areas for a specific neighbourhood type is higher (positive values), on par (around 0), or lower (negative values) compared to what would be expected based on the overall distribution of new homes between the different neighbourhood types. We calculate $\text{Diff}_{\text{per,nbh}}$ both for the current state as well as for the 2C, 4C and H++ CC scenarios to be able to estimate how the distribution of recently built homes in HFR areas is expected to shift between the different neighbourhood development trajectories with CC.

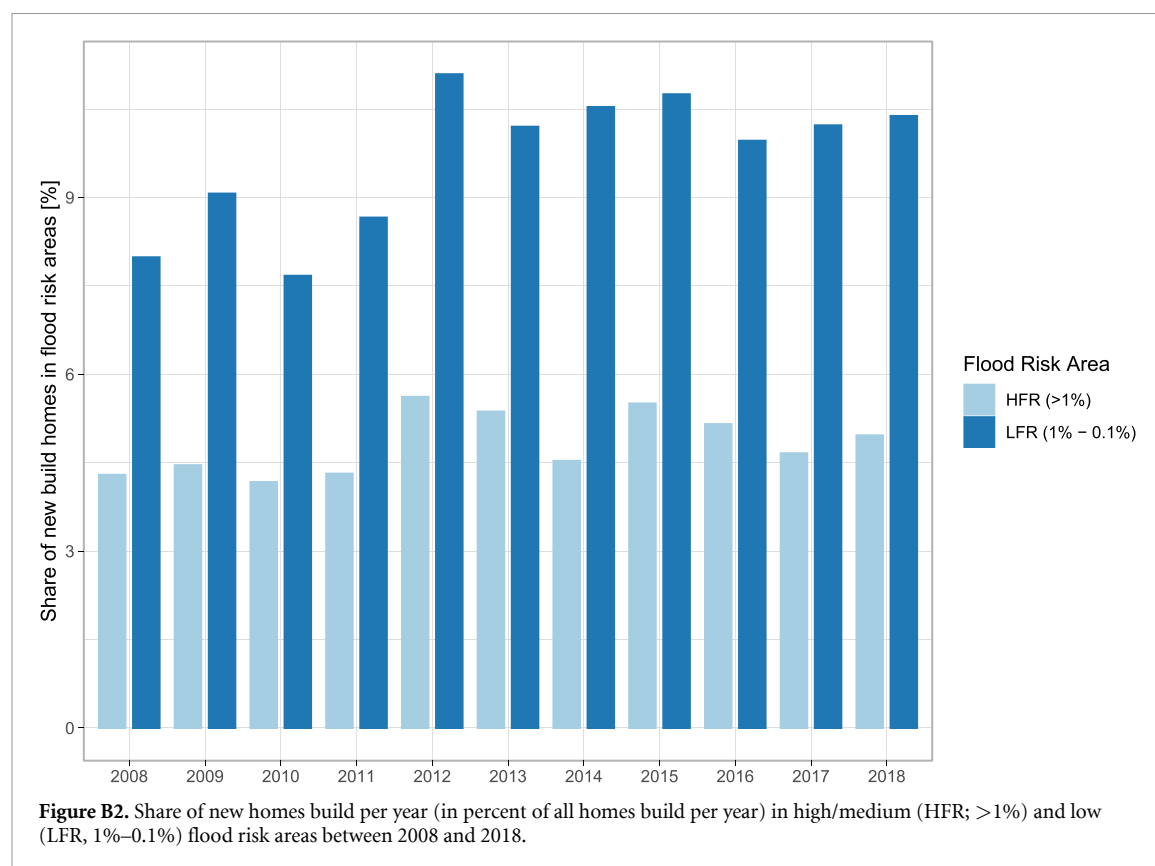
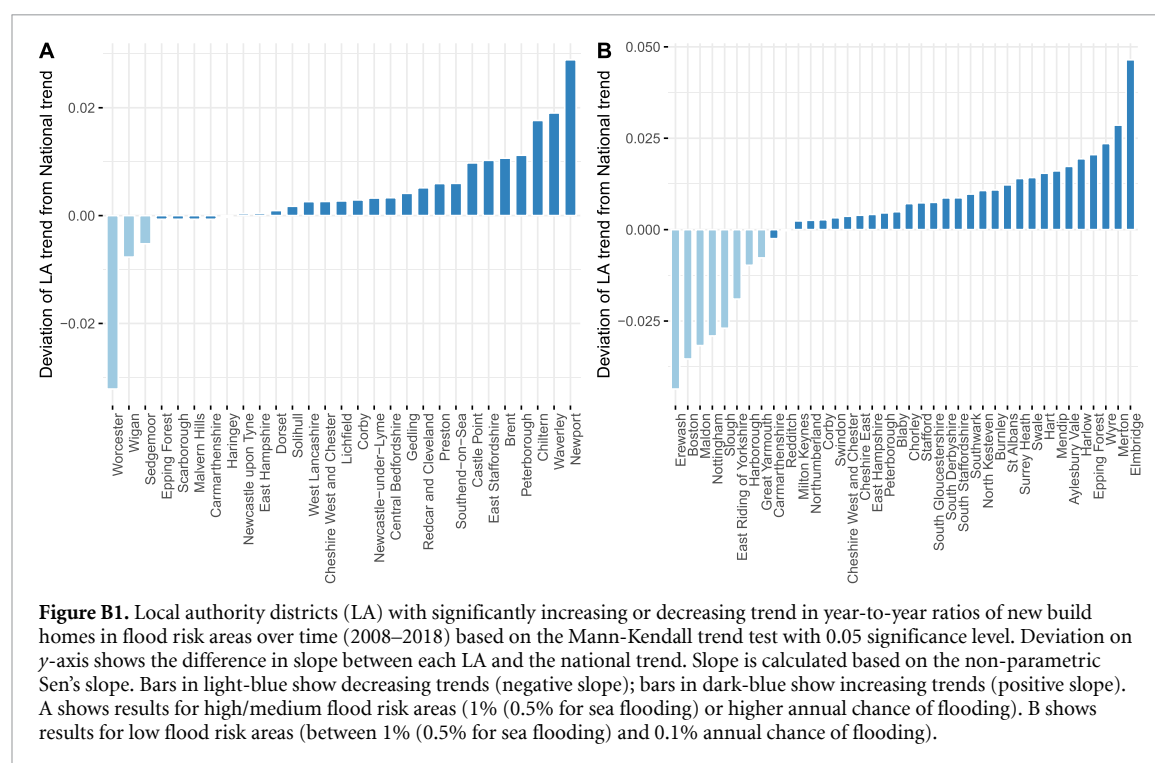
Appendix B. Results

B.1. Summary results

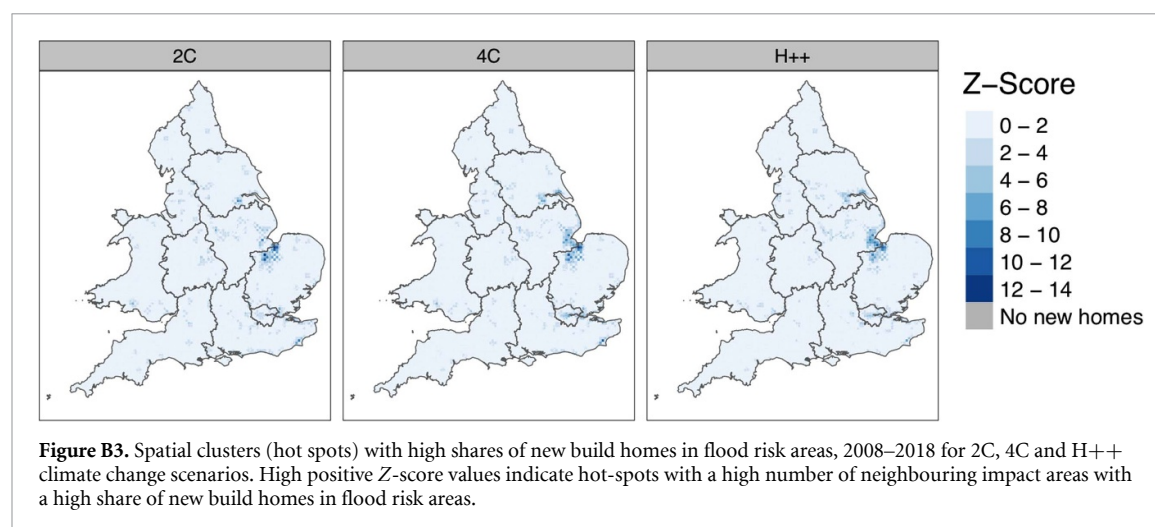
Table B1. Summary statistics showing all homes build in high/medium flood risk areas (1% or greater annual chance of flooding from rivers and surface water and 0.5% or greater annual chance of flooding from sea) and low flood risk areas (between 0.1% and 1% annual chance of flooding from rivers and surface water and between 0.1% and 0.5% annual chance of flooding from sea) by country, dwelling type and flood type.

	England				Wales				
	River	Sea	Surface	Multiple	River	Sea	Surface	Multiple	Total
High/medium flood risk area									
Houses (detached, semi-detached, terrace)	9850	935	12 483	2126	1120	40	513	224	27 291
Flats (self-contained)	15 403	1841	12 459	2335	289	171	223	54	32 775
Other	1035	95	1116	16	13	—	72	—	2347
Total	26 288	2871	26 058	4477	1422	211	808	278	62 413
Low flood risk area									
Houses (detached, semi-detached, terrace)	8515	5391	31 406	7175	1189	1938	1339	777	57 730
Flats (self-contained)	16 227	5011	30 452	6732	697	3112	500	746	63 477
Other	1221	198	2889	453	6	171	75	4	5017
Total	25 963	10 600	64 747	14 360	1892	5221	1914	1527	126 224

B.2. Time trends



B.2.1. Spatial trends and hot spots



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References

- [1] Field C B *et al* 2014 Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*
- [2] Stevens A J, Clarke D and Nicholls R J 2016 Trends in reported flooding in the UK: 1884–2013 *Hydrol. Sci. J.* **61** 50–63
- [3] Winsemius H C *et al* 2016 Global drivers of future river flood risk *Nat. Clim. Change* **6** 381–5
- [4] Roggema R 2010 *Adaptation to Climate Change: A Spatial Challenge* (Berlin: Springer)
- [5] Mehryar S and Surminski S 2020 The role of national laws in managing flood risk and increasing future flood resilience *Grantham Research Institute on Climate Change and the Environment Working Paper* vol 334
- [6] Keenan J M 2018 Types and forms of resilience in local planning in the US: who does what? *Environ. Sci. Policy* **88** 116–23
- [7] Meerow S, Newell J P and Stults M 2016 Defining urban resilience: a review *Landscape Urban Plan.* **147** 38–49
- [8] Davidson J L *et al* 2016 Interrogating resilience: toward a typology to improve its operationalization *Ecol. Soc.* **21** 27
- [9] Keating A, Campbell K, Mechler R, Magnuszewski P, Mochizuki J, Liu W, Szoenyi M and Colin M 2017 Disaster resilience: what it is and how it can engender a meaningful change in development policy *Dev. Policy Rev.* **35** 65–91
- [10] O'Hare P and White I 2018 Beyond 'just' flood risk management: the potential for—and limits to—alleviating flood disadvantage *Reg. Environ. Change* **18** 385–96
- [11] Begg C, Walker G and Kuhlicke C 2015 Localism and flood risk management in England: the creation of new inequalities? *Environ. Plan. C: Gov. Policy* **33** 685–702
- [12] Gillard R 2016 Questioning the diffusion of resilience discourses in pursuit of transformational change *Glob. Environ. Politics* **16** 13–20
- [13] Béné C, Mehta L, McGranahan G, Cannon T, Gupta J and Tanner T 2018 Resilience as a policy narrative: potentials and limits in the context of urban planning *Clim. Dev.* **10** 116–33
- [14] Walker G, Burningham K, Jane F, Smith G, Thrush D and Helen F 2006 Addressing environmental inequalities: flood risk *Technical Report* SC020061/SR1 Environment Agency, Bristol, UK
- [15] Werritty A, Houston D, Ball T, Tavendale A and Black A 2007 Exploring the social impacts of flood risk and flooding in Scotland
- [16] Fielding J and Burningham K 2005 Environmental inequality and flood hazard *Local Environ.* **10** 379–95
- [17] Kazmierczak A, Cavan G, Connelly A and Lindley S 2015 Mapping flood disadvantage in Scotland 2015: main report *Technical Report* PPDAS60523, The Scottish Government—Environment and Forestry Directorate, Edinburgh, UK
- [18] Walker G and Burningham K 2011 Flood risk, vulnerability and environmental justice: evidence and evaluation of inequality in a UK context *Crit. Soc. Policy* **31** 216–40
- [19] Sayers P, Horritt M, Penning-Rowell E and Fieth J 2017 Present and future flood vulnerability, risk and disadvantage: a UK scale assessment *Technical Report*, Sayers and Partners LLP for the Joseph Rowntree Foundation, Watlington, UK (available at: www.sayersandpartners.co.uk/uploads/6/2/0/9/6209349/sayers_2017_-_present_and_future_flood_vulnerability_risk_and_disadvantage_-_final_report_-_uploaded_05june2017_printed_-_high_quality.pdf)
- [20] Sayers P, Penning-Rowell E C and Horritt M 2018 Flood vulnerability, risk and social disadvantage: current and future patterns in the UK *Reg. Environ. Change* **18** 339–52
- [21] Montgomery M C and Chakraborty J 2015 Assessing the environmental justice consequences of flood risk: a case study in Miami, Florida *Environ. Res. Lett.* **10** 095010
- [22] Keenan J M, Hill T and Gumber A 2018 Climate gentrification: from theory to empiricism in Miami-Dade county, Florida *Environ. Res. Lett.* **13** 054001
- [23] Leitner H, Colven E and Sheppard E 2017 Ecological security for whom? The politics of flood alleviation and urban environmental justice in Jakarta, Indonesia *The Routledge Companion to the Environmental Humanities* ed U K Heise, J Christensen and M Niemann (Abingdon: Routledge) pp 210–21
- [24] Young D and Essex S 2020 Climate change adaptation in the planning of England's coastal urban areas: priorities, barriers and future prospects *J. Environ. Plan. Manage.* **63** 912–34

- [25] Koen de K, Filatova T, Need A and Bin O 2019 Avoiding or mitigating flooding: bottom-up drivers of urban resilience to climate change in the USA *Glob. Environ. Change* **59** 101981
- [26] Westcott M, Ward J, Surminski S, Sayers P and Bresch D N 2019 Physical risk framework: understanding the impacts of climate change on real estate lending and investment portfolios *Technical Report*, Cambridge Institute for Sustainability Leadership (CISL), Cambridge, UK
- [27] Surminski S, Mehryar S and Golnaraghi M 2020 Flood risk management in England *Technical Report*, Geneva Association, Zurich, Switzerland (available at: www.genevaassociation.org/sites/default/files/flood-risk-management-england.pdf)
- [28] Tesselaar M, Botzen W J and Aerts J C J H 2020 Impacts of climate change and remote natural catastrophes on EU flood insurance markets: an analysis of soft and hard reinsurance markets for flood coverage *Atmosphere* **11** 146
- [29] Prudential Regulation Authority 2015 The impact of climate change on the UK insurance sector - a climate change adaption report (London: Prudential Regulation Authority)
- [30] Merz B, Hall J, Disse M and Schumann A 2010 Fluvial flood risk management in a changing world *Natural Hazards and Earth System Sciences* **10** 509–27
- [31] Sayers P 2017 Evolution of strategic flood risk management in support of social justice, ecosystem health and resilience *Oxford Research Encyclopedia of Natural Hazard Science* (Oxford: Oxford University Press) (<https://doi.org/10.1093/acrefore/9780199389407.013.85>)
- [32] Environment Agency 2018 Managing flood and coastal erosion risks in England: 1 April 2011 to 31 March 2017 *Technical Report* Environment Agency, Bristol (available at: assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/694808/1_April_2011_to_31_March_2017_managing_FCERM.pdf)
- [33] Porter J and Demeritt D 2012 Flood-risk management, mapping and planning: the institutional politics of decision support in England *Environ. Plan. A* **44** 2359–78
- [34] MHCLG 2020 Planning for the future—white paper *Technical Report*, Ministry of Housing, Communities and Local Government, London, UK (available at: www.gov.uk/government/consultations/planning-for-the-future)
- [35] Hayes S, Barker A and Jones C 2014 Flood management consideration in sustainability appraisal and strategic environmental assessment in England and Scotland *J. Environ. Assess. Policy Manage.* **16** 1450025
- [36] ASC 2019 Progress in preparing for climate change—2019 progress report to Parliament *Technical Report*, Committee on Climate Change—Adaptation Sub-Committee, London, UK (available at: www.theccc.org.uk/wp-content/uploads/2019/07/CCC-2019-Progress-in-preparing-for-climate-change.pdf)
- [37] Sayers P B, Horritt M S, Penning-Rowsell E and McKenzie A 2015 Climate change risk assessment 2017—appendix E: adaptation levers: evidence base projections of future flood risk in the UK *Report for the UK Adaptation sub-Committee* Sayers Associates
- [38] Kovats R and Osborn D 2016 UK climate change risk assessment 2017: evidence report chapter 5: people & the built environment
- [39] Patias N, Rowe F and Cavazzi S 2020 A scalable analytical framework for spatio-temporal analysis of neighborhood change: a sequence analysis approach *The Annual Int. Conf. on Geographic Information Science* (Springer) pp 223–41
- [40] Gilbert R O 1987 *Statistical Methods for Environmental Pollution Monitoring* (New York: Wiley)
- [41] Getis A and Ord K 1992 The analysis of spatial association by use of distance statistics *Geogr. Anal.* **24** 189–206
- [42] Environment Agency 2019 What is the risk of flooding from surface water map? *Technical Report* Environment Agency, Bristol (available at: assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/842485/What-is-the-Risk-of-Flooding-from-Surface-Water-Map.pdf)
- [43] Finlay J and Bolton P 2020 Briefing paper CBP 8803—autumn and winter floods 2019–20 *Technical Report* House of Commons Library, London (available at: <http://researchbriefings.files.parliament.uk/documents/CBP-8803/CBP-8803.pdf>)
- [44] Buser M 2020 Coastal adaptation planning in Fairbourne, Wales: lessons for climate change adaptation *Plan. Pract. Res.* **35** 127–47
- [45] Sayers P B, Horritt M S, Penning-Rowsell E and McKenzie A 2015 Climate change risk assessment 2017—appendix E: adaptation levers: evidence base projections of future flood risk in the UK *Report for the UK Adaptation sub-Committee* Sayers Associates
- [46] ASC 2015 Progress in preparing for climate change 2015 Report to Parliament *Technical Report* Committee on Climate Change—Adaptation Sub-Committee, London (available at: www.theccc.org.uk/wp-content/uploads/2015/06/6.736_CCC_ASC_Adaptation-Progress-Report_2015_FINAL_WEB_250615_RFS.pdf)
- [47] Keating A, Campbell K, Szoenyi M, McQuistan C, Nash D and Burer M 2017 Development and testing of a community flood resilience measurement tool *Nat. Hazards Earth Syst. Sci. Discuss.* **17** 77–101
- [48] Jones L, Constan M A, Matthews N and Verkaart S 2021 Advancing resilience measurement *Nat. Sustainability* **1** 2
- [49] Bin O, Kruse J B and Landry C E 2008 Flood hazards, insurance rates and amenities: evidence from the coastal housing market *J. Risk Insur.* **75** 63–82
- [50] Beltrán A, Maddison D and Elliott R J R 2018 Is flood risk capitalised into property values? *Ecol. Econ.* **146** 668–85
- [51] Ordnance Survey 2019 AddressBase Premium (available at: www.ordnancesurvey.co.uk/business-government/products/addressbase-premium)
- [52] Office for National Statistics 2019 ONS Postcode Directory (available at: <http://geoportal.statistics.gov.uk/datasets/ons-postcode-directory-november-2019>) (Accessed 10 December 2019)
- [53] HRW 2015 Update analysis on the number of properties located in areas at risk from flooding and/or coastal erosion on England *Technical Report*, HR Wallingford, Wallingford, UK (available at: www.theccc.org.uk/wp-content/uploads/2015/06/MCM7406-RT001-R02-00-low-res.pdf)
- [54] Environment Agency 2020 Risk of Flooding from Rivers and Sea (RoFRS) (available at: data.gov.uk/dataset/bad20199-6d39-4aad-8564-26a46778fd94/risk-of-flooding-from-rivers-and-sea) (Accessed 10 April 2020)
- [55] Wales N R 2020 Risk of Flooding from Rivers and Sea (RoFRS) (available at: lle.gov.wales/catalogue/item/Rofras/?lang=en) (Accessed 10 April 2020)
- [56] Environment Agency 2020 Risk of Flooding from Surface Water Extent (RoFSW) (available at: data.gov.uk/dataset/8b82987d-3616-4e46-8edb-2973e8b82ad7/risk-of-flooding-from-surface-water-extent-1-percent-annual-chance) (Accessed 10 December 2019)
- [57] Natural Resources Wales 2020 Risk of Flooding from Surface Water Extent (RoFSW) (available at: lle.gov.wales/catalogue/item/RiskOfFloodingFromSurfaceWater/?lang=en) (Accessed 10 December 2019)
- [58] Sayers P B, Horritt M S, Penning-Rowsell E and McKenzie A 2015 UK climate change risk assessment 2017—evidence report—flood risk—appendix C—climate change projections *Projections of future flood risk in the UK. Report for the UK Adaptation sub-Committee* Sayers Associates